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ABSTRACT

The development of cavitation behind a disc in water and Freon-113 was investigated in a cavitation tunnel designed for this purpose. Measurements of pressure within the cavities formed in water indicated that the vapor pressure within the cavity was less than the vapor pressure of the fluid at the bulk temperature. Observations of the cavities formed in the two liquids showed qualitative differences, and some possible reasons for this behavior are discussed.

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I. INTRODUCTION

A prime requirement that must be met by pumps designed for use in modern liquid propellant rocket systems is low weight and small space. This requirement dictates the use of turbine driven pumps as the only pumping machinery capable of delivering the large flow rates at the head required and still remain within these limitations. In addition, the use of impulse turbines as the driving element has dictated high rotative speeds for the pumping machinery to eliminate heavy reduction gear trains between pump and turbine (1)*. These high rotative speeds, coupled with a head on the order of 20 atmospheres, produce high fluid velocities with respect to the pump impeller. In accord with Bernoulli's Law, the static pressure is reduced, generally to such a degree that it falls below the vapor pressure of the fluid being pumped. In this condition, the fluid is thermodynamically unstable and the condition is relieved by the formation of vapor bubbles on the impeller blading. The immediate effect of this phenomenon, called cavitation, is a reduction of pump output due to large fluid losses brought about by mixing and diffusion losses in the flow. In addition, cavitation erosion of the material of the impeller may be of major importance for large pumps where long life is required. The influence of the liquid properties on cavitation material damage is a subject of great current interest but will not be discussed herein, except to point out that there are no presently known parameters that insure similar rates of erosion for different fluids even for the same material. Finally, it should

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*Numbers in parentheses refer to the references at the end of the text.

be mentioned that while cavitation is particularly severe in propellant pumps because of the high rotative speeds, it is by no means limited to them. In fact, in nearly every case of a specific pump application, maximum speed is desirable for reasons of economy and size. Furthermore, many situations arise in the process industries, e.g., petroleum refining, in which highly volatile substances must be pumped and the effect of cavitation on pump performance is of prime importance.

From dimensional reasoning it is known that the non-cavitating performance of geometrically similar machines pumping liquids will be the same at corresponding flow rate coefficients, provided the Reynolds number remains the same. Under cavitating conditions, however, the flow geometry is distorted and performance may be significantly altered. In the hydraulic and hydrodynamic machinery literature, there are several cavitation similarity parameters that are used to interpret cavitation experiments. The first of these is a pressure coefficient (called the cavitation number, k, introduced by Prandtl) which is defined as the difference between the free stream static pressure and the cavity pressure (assumed to be the vapor pressure of the bulk fluid) divided by the free stream dynamic pressure. Another parameter used in pump and turbine work is the ratio of the total inlet head minus the vapor pressure of the flowing liquid to the non-cavitating head (introduced by Thoma and denoted by σ). A third similarity parameter, again in wide use in the pump field, is the "suction specific speed", S, due to Bergeron, which relates the pump speed, flow rate and inlet total head minus the vapor pressure of the fluid. It can be shown that these

similarity parameters are simply related, and further, that if the operating point of a pump is fixed, constancy of σ implies constancy of k and S. These parameters enjoy widespread use, and in the case of pumping cold tap water, or even liquid sodium, have been proved to give accurate scaling of cavitation performance from one speed to another, and from one pump to another of the same design but different size.

In most of the experimental work to date, it has always been assumed that the pressure in the cavity is equal to the vapor pressure of the fluid at the bulk temperature. Some investigation of this assumption is in order since recent experimental work on pumps operating with hot water, some hydrocarbons, and cryogenic fluids shows that there are marked differences in cavitating performance with the different media. Stahl (2) has compared the performance of the same pump with cold water and water at 294°F, with constant speed and flow rate, and has found the cavitating performance with the hot water significantly better. In particular, the inlet pressure to obtain the same reduction in efficiency due to cavitation was lower by about 1.5 psi for the hot water than the cold. The possibility immediately suggested is that the cavity pressure is lower than the bulk fluid vapor pressure, producing a higher cavitation number and thereby a less severe condition to be met by the pump. Various physical models of the flow that can account for this effect can be proposed. One is that a stable cavity is attached to the leading edge of the blade, as seen in water tunnel observations of cavitating hydrofoils. It seems reasonable to assume that the turbulent closure process at the end of the cavity entrains the vapor within the cavity and carries it downstream.

To maintain the cavity, therefore, liquid must be evaporated into it from the surrounding flow. The removal of the latent heat of evaporation required for this process cools the boundaries of the cavity, thereby causing a local decrease in the vapor pressure of the fluid. According to whether the vapor density, latent heat of evaporation, and rate of entrainment are large or small, the cooling effect may be large or small. A different, and one equally likely model, is that cavitation occurs in the bulk of the liquid as the nuclei present in the flow move into the regions of low pressure and grow there. Their rate of growth is dependent upon the degree of superheat acquired in the low pressure regions and on other physical properties of the fluid.

Researchers in the field (2, 3, 4, 5) have devoted considerable effort to establish the correct similarity laws for cavitating flows with various liquids. Most of these workers have taken a simpler view; namely, that in the cavitation process a certain amount of vapor is formed within the pump inlet, and that for similar cavitating performance, the ratio of the volume of vapor formed to the volume of the vapor-liquid mixture must be the same. It is not made clear, however, to what portion of the flow this ratio is to be applicable. It is also assumed that the vapor and bulk fluid are in thermal equilibrium. Evaporation of the liquid is accompanied by a reduction in temperature of the bulk fluid with a correspondingly reduced vapor pressure. The reduction in vapor pressure for a given ratio of vapor-to-liquid volume will depend only upon the thermodynamic properties of the fluid, and the fluid

will be said to have a high or low tendency to cavitate as the depression in vapor pressure is low or high, respectively. Alternatively for a given depression of the vapor pressure, the vapor-to-liquid volume ratio is said to indicate the tendency of a fluid to cavitate (3)*.

Based on these considerations, Jacobs (4) is able to correlate to a reasonable degree the cavitating performance of a machine pumping liquid hydrogen and liquid nitrogen. Salemann (5), however, as a result of his experiments with butane, Freon-11, and water, challenges the use of the vapor-to-liquid volume ratio as a criterion for cavitation similarity, stating that this ratio need not apply to the entire flow field but only to the liquid adjacent to the cavity, and that therefore the constancy of the vapor-to-liquid volume ratio does not imply similar cavitating conditions with different liquids.

In the purely thermodynamic approach to cavitation similarity, neither time nor size scales are considered, and it is difficult to imagine that they do not enter into the cavitation process. The average time spent by a particle in the low pressure regions of the impeller is a few milliseconds; as Plesset and Zwick point out (6), this time is of the same order as that needed to grow a nucleus in water to appreciable size with moderate superheat. Previous history of the fluid, too, may be important in its effect on concentration of nuclei and hence on cavitating performance (7).

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*The ratio of the volume of vapor formed to that of the liquid for a depression of the vapor pressure of one foot (of head) can be shown to be (4) $B = (c_p T/J)(v_g/v_f \lambda)^2$ where c_p is the specific heat of the liquid, T the absolute temperature, λ the latent heat of evaporation. v_g the specific volume of the vapor and v_f that of the fluid.

It is possible, however, that the dynamics of individual bubble growth may, in some instances, produce the vapor-to-liquid volume ratio evolved from the pure static thermodynamic considerations used in references (2) to (5).

It is with the intent of learning more about the physical mechanics of the cavitation phenomenon that this experiment is undertaken. Major objectives are the following: (1) to observe cavities in water, the most common fluid subject to cavitation, and to compare these cavities with cavities of the same length in Freon-113 (trichlorotrifluoroethane, b.p. 117.6°F), which was chosen for convenience in filling, pressurization, etc., as well as being typical of hydrocarbon compounds. The temperature, pressure, flow velocity and cavitation number will be varied to determine if any qualitative differences are apparent; (2) to measure the pressure within the cavity to determine whether it is, in fact, less than the vapor pressure of the bulk fluid. It will not be until information of this type is available that realistic models of the flow can be made or the proper parameters describing the cavitation process found. For the purpose of the present investigation it was decided to observe the formation and development of the cavitation behind a disc normal to the flow. The principal reason for this choice is the relatively simple geometry of the flow and the fact that long cavities can be created (thereby increasing the likelihood of measuring the cavity pressure successfully).

In the sections that follow the apparatus used for the experiments is described and the results obtained thus far outlined.

The report is concluded with some observations on the flow models previously discussed, together with suggestions for improving the equipment.

II. EXPERIMENTAL APPARATUS

A. Facility Description

The test facility was designed and built at the Hydrodynamics Laboratory at the California Institute of Technology for the purpose of making studies of the cavities formed by a small disc mounted in a transparent working section. The facility was a closed hydraulic circuit consisting of a cylindrical stilling chamber, the test section, a diffuser, a recirculating pump and a system of return piping together with suitable instrumentation to measure pressure, temperature and flow rate of the working medium, and pressure within the cavity. Means of controlling system pressure, temperature and flow rate were also provided. Fig. 1 shows the general features of the system.

The stilling chamber was an 18 inch length of standard weight 12.75 inch O.D. steel pipe. The end plates were of 3/4 inch steel plate and were held to the chamber with Victaulic couplings. Mounted within the chamber was the apparatus required to determine cavity pressure; namely, a six inch "U" tube mercury manometer, one leg of which was connected to a pressure-tight cylindrical brass vapor pressure bomb containing some of the working fluid. The other manometer leg was connected to a hollow 0.106 inch I.D. stainless steel probe which extended into the cavity formed during operation, and which also served as the support for the small disc that created the cavity. Valves were installed to connect the manometer to the cavity, to purge lines and to the vapor pressure bomb. They were of a push-pull type utilizing "O" ring seals and were designed to minimize fluid entrapment. Connecting lines were of 1/4 inch copper tubing. The probe was supported in the stilling chamber by a

streamlined brass strut. The mercury manometer was observed through a pyrex glass window in the side of the stilling chamber. The general internal arrangement of the stilling chamber is shown in Figs. 2, 3 and 4. A schematic drawing of the piping diagram to obtain the cavity pressure is shown in Fig. 5; and a view of the probe and disc appears in Fig. 6.

The working section provided to view the flow was 1.177 inches I.D. and four inches long, and was made of pyrex glass. The inlet to the working section from the stilling chamber was a faired bell mouth with a radius of one-and-a-half working section diameters. Three contiguous layers of brass screen of 30, 60 and 90 mesh, respectively, were located in the stilling chamber upstream of the bell mouth to damp some of the turbulence and provide a smooth inlet flow to the test section.

In these tests the cavity was formed by a sharp-edged disc fabricated from stainless steel; the upstream face was 0.18 inch in diameter and the disc was 0.062 inch thick. The probe extended 0.25 inch downstream of the upstream face of the disc (see Fig. 5), and was belled slightly to prevent droplets of the working fluid from entering the line to the manometer and giving an erroneous pressure indication.

The diffuser was fabricated from two standard steel reducers, one of 12° included angle and the other of 8° included angle. The flow was diffused from the 1.177 inch diameter of the working section to the 2 1/2 inch pipe I.D. of the recirculating system in sixteen inches. Flanged joints with "O" ring seals were used at both ends of the diffuser.

A 66 inch length of the piping leading to the pump intake was encased in standard three inch steel pipe with suitable seals to form a heating jacket. House saturated steam at 50 psig (max.) was used as the source of heat. A seven inch length of the piping immediately upstream of the stilling chamber was wrapped with 20 turns of 1/4 inch copper tubing to form a cooling coil. Tap water was used as the cooling medium. Steady state temperatures in the range of 70-250° F could be established in the working fluid with this arrangement.

A propeller type flow meter manufactured by the Waugh Engineering Company was installed in the circuit upstream of the cooling coil.

The fluid was circulated by a centrifugal pump driven by a three horsepower, three phase electric motor. The pump speed was regulated by a "variac" control; at full speed the pump discharged the working fluid through the test section at a velocity of approximately 20 feet per second.

The pressurizing system consisted of a neoprene bag suspended within a pressure-tight cylindrical steel vessel 7 1/2 inches in diameter and 9 inches long. The neoprene bag connected to the bottom of the stilling chamber. A compressed air source available in the Hydrodynamics Laboratory connected, through a pressure regulator, to the portion of the vessel external to the neoprene bag.

For the purposes of deaeration of the working fluid and operation of the facility under vacuum, a vacuum source available in the laboratory was connected to the high point of the stilling

chamber. Air withdrawn from solution was removed from the circuit through three bleed valves, of push-pull design utilizing "O" ring seals, located at the circuit high points.

All components of the facility fabricated from steel were galvanized; and the entire hydraulic circuit was lagged to a minimum 3/4 inch thickness.

B. Instrumentation

System pressure was obtained from a bank of three water-mercury manometers with the piezometer opening at the stilling chamber. For experiments utilizing a working fluid other than water, a cylindrical brass interface pot was provided. The finite height of the manometers precluded system operation above 65 psia. All pressure readings were taken to the nearest 0.01 inch.

System temperature was taken from a calibrated laboratory thermometer mounted in a two inch depression in the stilling chamber wall. The thermometer bulb was encased in an oil bath. Temperature readings were taken to the nearest 0.1° C in the water experiments, and to the nearest 0.1°F for the Freon-113 experiments.

The flow meter was used in conjunction with a Hewlett-Packard electronic counter. The output signal of the flow meter required electronic amplification to actuate the counter properly. Flow rates were recorded as the average of 10 periods of revolution of the flow meter propeller and then converted to cubic feet of flow per second. The flow meter was calibrated by means of a volumetric tank. Ten period average readings were made to the nearest 0.01 milliseconds which, near maximum flow rate, corresponds to

a difference in velocity through the test section of 0.025 feet per second.

Pressure differential readings between a vapor bomb and the cavity were made on the standard six inch "U" tube mercury manometer mounted within the stilling chamber. Readings were made to the nearest 0.05 inch. The vapor pressure bomb, filled with a deaerated sample of the working fluid and surrounded by the flowing working fluid at the selected temperature, served as a reference against which the cavity pressure was measured.

C. Photographic and Lighting Facilities

Still photography was the only photography employed throughout this investigation. A 4 x 5 inch view camera was used and an Edgerton-type flash unit with a flash duration in the order of four microseconds was employed for lighting the working section.

Lighting for visual observation of the manometer within the stilling chamber was provided by four standard flashlight bulbs, water-proofed with neoprene paint, mounted to the manometer frame.

III. EXPERIMENTAL PROCEDURE

A. Preparation of the Facility for Experimental Runs

Before any measurements were taken it was necessary to fill the vapor bomb within the stilling chamber with a deaerated sample of the working fluid. Deaeration with both the water and Freon was accomplished by filling the bomb to capacity and, by a combination of slow boiling and agitation, driving dissolved air from solution. When approximately one-half of the volume of fluid remained, the bomb was immediately sealed. The extent of deaeration and purity of the sample were determined by bringing the bomb and the surrounding working fluid to equilibrium at a fixed temperature and measuring the pressure of the vapor within the bomb with an absolute manometer. Comparison with tabulated vapor pressure versus temperature data then indicated, qualitatively, at least, the extent of deaeration. For the water sample, the pressure measurement made at 68.0°F was identical with the tabulated value of vapor pressure for pure water. For the Freon sample the measured pressure at 79.0°F was 6.874 psia, 0.119 psia above the tabulated vapor pressure at that temperature, indicating that some air might still be dissolved in the Freon. Due to the press of time, however, no further attempts to reduce air content in the Freon sample were made.

It was also found necessary to deaerate the working fluid as far as possible to eliminate the effects caused by air diffusion into the cavity and to obtain a reasonably homogeneous, single phase flow of liquid which, among other things, would ensure that the propeller flow meter would indicate true fluid flow rate. The deaeration

of water was accomplished by reducing the absolute pressure within the system to a value as low as possible, about two pounds per square inch, absolute, and slowly recirculating the fluid through the circuit. At intervals of approximately ten minutes the circulation was stopped, the vacuum relieved and the air removed from solution. The process was continued until the air content was reduced below the arbitrarily set figure of 2.0 ppm which was approximately 7.9 percent of saturation air content of water at 20°C. For the Freon-113 experiments deaeration of the bulk was not attempted.

The air content was measured by the Van Slyke Blood Gas Apparatus (Central Scientific Co.).

B. Cavitating Studies with Water

Two types of experiments were made. In the first, the vapor bomb-cavity pressure differential was measured for a range of temperatures from ambient to approximately 118°C, the maximum attainable with the heat source available. In the second type, conditions of pressure and flow rate required to form cavities of arbitrary but fixed length at fixed temperature were measured for the same range of temperatures as the first set of runs.

Prior to the start of a run of the first type, the barometric pressure, air content and water-mercury manometer tare readings were observed and recorded. The working fluid was then brought to the desired temperature and maintained there for approximately 15 minutes to insure thermal equilibrium within the system. The pump was brought to maximum speed and pressure adjusted to allow a cavity to form on the disc. With the cavity formed, the probe

and connecting tubing were purged by vacuum; and by the proper manipulation of valves, the interior manometer was opened, the reading observed and recorded. Conditions of working fluid pressure, temperature and flow rate existing at the moment the interior manometer was read were likewise recorded.

For the runs of the second type, cavities of length 13/16 inch and 1 3/8 inches, approximately, were formed at each temperature. Barometric pressure, air content and water-mercury manometer tare readings were observed and recorded; and thermal equilibrium established within the hydraulic circuit at the selected temperature. Pump speed was increased to nearly maximum flow rate, the pressure adjusted to allow a cavity to form. Final adjustment of the cavity to the length desired was made with the "variac" pump speed control. Working fluid pressure, temperature and flow rate were observed and recorded. Photographs of the cavities for one such series of runs were made.

Major limitations of the system became apparent in the initial attempts to obtain the cavity pressure readings.

First, the limitations of pump capacity precluded velocities through the test section higher than 19.8 feet per second. After increasing pump submergence by seven feet and stripping and regalvanizing all circuit piping, this velocity remained essentially unchanged.

Second, the hydraulic circuit could not be made to hold a vacuum sufficiently well so that over prolonged periods at pressures below atmospheric, the air content of the working fluid

would not increase. After a series of runs at elevated temperature was concluded, the hydraulic circuit was sealed and allowed to cool overnight. Air content measurements the following morning, without exception, indicated that air content had increased by a minimum factor of two over that measured preceding the runs of the day before. A considerable portion of each day's experimentation time, therefore, was spent in deaerating the working fluid. One or more of the four 2 1/2 inch Victaulic couplings in the circuit, replaced by flanged joints prior to the Freon experiments, were suspected of malfunction.

Due to the low attainable fluid velocity in the test section, it was impossible to form a cavity, at temperatures below 98°C, without reducing the system pressure to the point where the bulk fluid commenced to boil; that is, fully developed cavity formation and boiling of the bulk fluid appeared to occur simultaneously. Similar performance was obtained with the system under pressure at temperatures over 100°C. In both regimes of operation the resulting froth frequently obscured the cavity and made the reliability of cavity pressure and flow rate readings questionable. A third limitation of the system, then, was the inability to control the level of pressure on the system closely enough to separate cavity formation from bulk fluid boiling.

As a result, further experimentation at temperatures below 98°C was abandoned.

C. Cavitating Studies with Freon-113

Extensive rework of the facility followed the water experiments: the Victaulic couplings, except those at the stilling chamber

ends, were replaced by flanged joints, the pump was lowered by seven feet, the circuit piping de-scaled and regalvanized, and a "softer" pressurizing system, shown in Fig. 7, installed. The velocity in the working section, however, did not increase as hoped; and the new pressurizing tanks were abandoned in favor of the original system due to failure of the large neoprene bag. Severe time limitations precluded relagging the entire circuit; therefore, only the stilling chamber and the piping immediately upstream and downstream of it were lagged to a minimum 3/4 inch thickness.

Experiments similar to those performed with water were attempted in the range 90 - 180°F.

Prior to runs made to determine cavity pressure, the barometric pressure and water-mercury manometer tare readings were observed and recorded. The Freon-113 was then brought to the desired temperature with flow rate at the maximum. It was found necessary to seal the circuit from atmosphere even below the boiling temperature, 117.6°F, to prevent loss of Freon by overflow through the stilling chamber's atmospheric vent. Throughout the range of temperature and ambient pressure, however, a cavity longer than four inches could not be produced. For cavities of that length, the backflow within the cavity caused by the re-entrant jet seen in Fig. 13 entered the probe in a continuous stream, and the probe could not be purged to make the pressure measurement. Cavity pressure measurements, therefore, were not made.

In the second type of test, cavities of length 13/16 inch and 1 3/8 inches, approximately, were formed at each temperature. Barometric pressure and water-mercury manometer tare readings were observed and recorded, and thermal equilibrium was established within the system at the selected temperature. A cavity of the desired length was formed by varying pump speed. Working fluid pressure, temperature, and flow rate were observed and recorded. Photographs of each cavity at each temperature were made.

D. Estimation of Errors

The errors involved in the determination of the cavitation numbers include errors in flow rate measurement, errors in pressure measurement and errors in temperature measurement. From considerations given in Reference (8) regarding minimum cavitation numbers derived from disc-to-test section diameter ratios, minimum cavitation numbers of about 0.300 were expected in the water experiments. It is obvious from the tabulated data, then, that serious errors were made in the measurement of the primary variables.

For the water experiments the source of maximum error is believed to be in the measurement of flow rate by the propeller flow meter. An attempt to check the readings of the flow meter by measurement of static pressure at the inlet of the test section was made. The alternate system, however, produced results obviously in error (large negative cavitation numbers) and its use was discontinued. The flow meter errors were believed to be caused by the through flow of air and/or vapor bubbles. The passing of froth

through the flow meter would cause it to indicate a higher-than-actual flow rate. The error thus introduced into the dynamic pressure would produce low cavitation numbers such as appear in Table I. Taking Run 2 of Table I as an example, a change of only -0.27 psi in the dynamic pressure (-1.0 fps in velocity) will raise the computed cavitation number from 0.111 to 0.316, a figure which is nearer to that expected. With the large amounts of froth that were frequently visible in the working section, an error of such magnitude is considered entirely possible.

Measurements of system pressure, though carefully made, are considered to be a second possible source of major error. Oscillation of the water-mercury manometers by $\pm$ 0.10 - 0.40 inch required that an average reading be recorded. The relatively small volume of the circuit (19 gallons) coupled with the "hard" pressurizing device, made the system sensitive to pressure changes induced by the cavitation process at the disc; manometer oscillations, therefore, were not smooth and accurate reading was thereby made difficult. Errors in system pressure measurement amounting to 18 percent of the dynamic pressure could easily have occurred, with an attendant and significant error in the cavitation number.

Temperature measurement errors are considered possible due to non-equilibrium conditions within the hydraulic circuit. Cavitation number sensitivity to temperature is such that at water temperatures of 110°C an error of $\pm$0.2°C changes the assumed cavity pressure by one one percent. Since the vapor pressure within the cavity is subtracted from the static pressure at infinity in the system, this small error can introduce a greater error in

the absolute difference and hence in the cavitation number. An error as high as $\pm 0.2^{\circ}C$ is considered unlikely and the errors thus introduced are estimated to be small for cavitation numbers above 0.300.

For the Freon-113 experiments, essentially the same sources of error were possible.

The flow meter is assumed to have given more accurate flow readings since the frothing, which was so troublesome in the water tests, was not detected in the Freon tests. Any errors in flow measurement, then, were those inherent to the instrument itself and are considered negligible.

Pressure measurement difficulties were again encountered due to the erratic oscillation of the water-mercury manometers; an error of 0.375 psi, considered the maximum possible, would amount to 11.6 percent of the dynamic pressure and produce a possibly serious error in the cavitation number.

As with water, the errors introduced through incorrect measurement of temperature are considered small since a $\pm 0.2^{\circ}F$ error produces a vanishingly small change in the assumed cavity pressure.

The errors in cavity pressure measurement are those inherent, again, to making an average reading of an erratically oscillating manometer. However, several readings were made at each test point and averaged with an error estimated not to exceed 1.5 percent.

IV. RESULTS AND DISCUSSION

The results of the experiment are presented in Tables I through VII wherein temperature, pressure, flow velocity, cavitation number, cavity pressure differential, when measured, and approximate cavity length, when measured, are given for each run. Photographs of the cavities obtained for the runs in Table VI for water and Table VII for Freon-113 are presented in Figs. 8 through 29.

The development of the cavities behind the disc was observed and is described as follows: a region of separated flow and slowly recirculating fluid, called the wake, occurred behind the disc; and if the static pressure of the flow was sufficiently high, no cavitation could take place. A general underpressure existed in the wake, however, due to the separated flow there; and as the static pressure of the fluid was gradually lowered, bubbles commenced to appear when the local pressure became equal to or less than the vapor pressure of the fluid. This condition, usually termed incipient cavitation, appeared as a white cloud or froth behind the disc, extending downstream a few disc diameters, and was perhaps two disc diameters in diameter. The cavitation now merely served to make the flow visible and did not change the external flow pattern. As the static pressure was lowered further, the volume of the vapor formed was sufficient to alter the external flow, and the size of the "bubble" behind the disc increased. At this stage, the cavitating wake still consisted of a great number of small vapor (and possibly air) cavities perhaps one-half a millimeter in diameter as reference to Fig. 8 will show. (In all of

the cavitation photographs the flow proceeds from left to right and the disc is just out of view.) With further decrease in the upstream static pressure, these bubbles grew larger and the entire cavitating region behind the disc expanded. At a stage when the overall length of the cavity was about eight disc diameters, the interior of the cavity, in water at least, became relatively free of froth and a fairly clear cavity was formed as in Fig. 13. A significant feature of these cavities was the re-entrant jet that formed intermittently (barely visible in Fig. 13) and impinged upon the back side of the disc itself, resulting in considerable difficulty in measurement of the pressure within the cavity. Continued reduction of the static pressure finally resulted in a classical free streamline flow with the fluid boundaries of the cavity becoming parallel to the walls of the duct. The disc used in the experiments was 0.17 of the test section diameter, and according to calculations of Reference (8) this limiting or "choking" cavitation number was k = 0.300. With water as the fluid medium this condition was easy to obtain for all ambient temperatures (room temperature to 245°F).

Photographs of the cavities were made at several temperatures and as already mentioned, cavity lengths of about 13/16 and 1 3/8 inches were selected for this purpose as being representative. It will be noticed in the water cavity photographs, Figs. 8 through 17, that while the flow is relatively free of bubbles being recirculated at the lowest temperatures, they stream through the working section profusely at the maximum temperature of 245°F. This is due to the imperfect deaeration of the water; and since bicarbonate scale had formed in the return pipes, carbon dioxide

undoubtedly was being evolved as well. Nevertheless it is interesting to observe that the appearance of all the long cavities is about the same, except possibly for 245°F, Fig. 12, even though free bubbles are being circulated. In each case the cavity terminates fairly cleanly with little visible entrainment taking place. The surfaces of these cavities are rough, indicating that the free stream flow is turbulent, although some of this may have come from the boundary layer developed on the disc support, Fig. 6.

In a similar series of photographs in Freon-113, Figs. 18 through 29, it is interesting to note that for all conditions of temperature and pressure represented, no free bubbles appear to be circulating through the circuit in distinction to the experience with water. In addition, no effort was made to deaerate the bulk Freon. Thus, the air present in solution, about 50 ppm, only comes out with difficulty; or if it does, it goes back into solution immediately and does not appear in the flow. The general development of the Freon cavities is more or less the same as that described for those in water; but several outstanding differences become immediately apparent. The amount of vapor entrainment at the closure of the cavity is much greater in Freon than in water and it increases with increasing temperature. A clear cavity is never observed in Freon; it always appears to be filled with a froth of minute bubbles. Finally, though this is less certain, the boundaries of the cavity are not nearly as well defined as in the case of the water cavities.

As a further comparison, the vapor-liquid volume ratio, B (see p. 5), was computed for the two sets of experiments. This

parameter ranged from about 0.7 to 2.5 for water, corresponding to a temperature range of 245°F to 205°F and about 0.28 to 3.8 for Freon with a corresponding temperature range of 180°F to 95°F. The value of B for cold water (68°F) is 3300 by way of comparison. Thus, considerable overlap of this parameter exists between the experiments and it is possible to compare these photographs at several different values of B. Thus, Figs. 13 and 20 have a value of B equal to 2.0; Figs. 16 and 27 have a value of 1.0; and Figs. 12 and 28 have a value of 0.65. It is clear from this comparison and from the foregoing remarks that the cavitation process is quite different in the two fluids; and, moreover, that the vapor-liquid volume ratio for a vapor pressure depression of one foot (B) does not imply "similar" cavitation.

The series of photographs described above were all taken at about the same cavity lengths by adjustment of the system pressure, temperature and flow velocity. If there were no vapor pressure depression, the cavitation number, whatever the fluid, should be the same, assuming no Reynolds number effects. Examination of Tables I through VI reveals an extremely erratic behavior of the cavitation numbers computed for the experiments with water. This behavior can be attributed only to error introduced through inaccuracies in measurement of the primary variables, as discussed in Experimental Procedure. Although these measurements were made carefully, it is concluded that certain systematic errors occurred, for even discounting the scatter of the data, it is very unlikely that cavitation numbers below the minimum choking cavitation number can be achieved. One of the fundamental difficulties in this measurement is that the dynamic pressure corresponding to a flow velocity

of 19 feet per second is only 2.4 psi (in water). At a temperature of 250°F an error in ambient temperature of one degree will cause an error in the vapor pressure of 0.49 psi, an appreciable percentage of the dynamic pressure. A similar figure is true for the Freon as well. Temperature errors of this magnitude are not believed to have occurred, but it serves to indicate the difficulty of the problem. The vapor pressure of the fluid at the bulk temperature, i.e., that in the vapor pressure bomb, could not be measured directly, either, at these temperatures, since it was usually at temperatures in excess of room temperature, the temperature of the laboratory manometers, and condensation could result.

It has not been possible, therefore, to measure the effects of temperature or fluid properties on the cavitation number. Thus, while cavities of the same length in the working section should have the same cavitation numbers based upon the pressure in the cavity, the cavitation number based upon the bulk vapor pressure may be considerably in error. These experiments, however, were unable to test this point.

Of more direct interest is the pressure difference between the cavity and the vapor pressure bomb. The bomb, in thermal equilibrium with the flow, provides a direct measure of the vapor pressure of the fluid without the necessity of deducing the vapor pressure from bulk temperature measurements; and, more important, makes it possible to measure the cavity pressure. Previous attempts to measure the cavity pressure by means of external manometers maintained in a "hot-box" proved futile at the elevated temperatures of this experiment. Measurements of this

pressure differential for the water tests, reported in Tables I through IV, indicate that the cavity pressure is consistently lower than the pressure of the vapor within the bomb. Though they are not consistent at the same bulk temperature in every case, the effect is consistently present. This differential pressure is on the order of 0.5 inch of mercury or 0.25 psi, which is about one-eighth of the dynamic pressure of the flow. The cavity pressure is not constant but fluctuates on the order of one-half inch of mercury, indicating that considerable entrainment of the vapor takes place. Moreover, it was possible to cause the cavity to disappear entirely by bleeding off the vapor to a low pressure source (the working section velocity and pressure were kept constant), which supports the notion that the evaporation rate into the cavity is limited. Thus, if appreciable vapor entrainment into the flow at the rear of the cavity takes place, a significant vapor pressure depression can result.

These measurements could be made only with a choked flow, i.e., the cavity extended downstream far beyond the test section, into the diffuser. It was only then possible to purge the lines to the internal manometer to get reliable cavity pressure readings. With shorter cavities, Fig. 13 for example, the re-entrant jet continuously filled the piezometer opening and no pressure measurements could be made. It seems quite probable that the vapor entrainment rate and vapor pressure depression are different for the shorter cavities; but this point could not be established with the present geometry.

The implication is clear from the above results that if the amount of the pressure differential varies from one fluid to another

at the same temperature, or if it changes with increasing temperature, similar cavitating performance of a given pump cannot be expected to result if the cavity pressure is taken to be the vapor pressure of the bulk fluid.

Measurements of the cavity pressure were also attempted with Freon-113. It was found that it was not possible to obtain a cavity longer than about four inches for any combination of temperature, pressure or velocity available for the system. The internal cavity pressure measuring system could not be adequately purged for this condition, i.e., the cavity was never free of liquid froth. Therefore, a direct comparison of vapor pressure depression in the two liquids could not be made.

The inability to create a cavity in the Freon longer than four inches is, in itself, most interesting. In one attempt to create a cavity long enough to make a pressure reading, for example, the tunnel was brought to thermal equilibrium at 90°F and vacuum sufficient to produce visible boiling of the Freon in the stilling chamber applied. With a flow velocity of approximately 19.6 feet per second under these conditions, it was still not possible to produce a cavity longer than four inches. Though no pressure measurement could be made, this phenomenon may be explained by the existence of a depression of the vapor pressure in the cavity similar to that observed in water, but large enough to prevent the formation of a choked cavity in the tunnel.

V. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The principal findings of this experiment may be cited as the following: a depression of the pressure in the cavities formed in water below the vapor pressure of the fluid at the bulk temperature does occur. The dependence of this effect on velocity could not be determined. Direct confirmation of this result in Freon-113 could not be established due to experimental difficulties; but it is inferred from the behavior of the cavity. The cavitation processes, as determined from photographs, in Freon-113 and hot water do not appear to be the same. The Freon cavities appear more frothy than do those in water; and the entrainment of the contents of the Freon cavities into the flow is much greater than observed for water. The vapor-liquid volume ratio for a vapor pressure depression of one foot, a commonly used cavitation similarity parameter, does not insure a similar cavitation process in two different fluids. However, it cannot be concluded from this that the cavitating performance in a pump will be different.

These findings should be regarded as a progress report on the study of cavitation similarity. The experimental apparatus used has self-evident limitations. Foremost among those in need of correction before further work can be done are the following: a higher velocity through the working section is needed. A pump delivering about three times the present flow rate should be installed to decrease the error of the cavitation number determination, and to vary the fluid velocity systematically. An improved system of pressurization is needed. The volume change of the fluid due to temperature and pressure changes causes the system pressure

to change because of insufficient ullage, i.e., the system is too "hard". Installation of a large, air-pressurized auxiliary tank equipped with a separating bladder, Fig. 7, should solve this problem.

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TABLE I

CAVITATION NUMBERS AND CAVITY PRESSURE MEASUREMENTS FOR WATER EXPERIMENTS

Initial Air Content: 4.1 ppm

Barometric Pressure: 29.31 in. Hg

Cavity Length: Indefinite

Run	T °C	System Pressure Above Atmospheric in. Hg	Flow Velocity in Test Section ft/sec	Cavity Pressure Differential* lb/in^2	Cavitation Number k
1	97.8	2.53	19.45	0.245	0.056
2	97.8	3.05	19.83	0.147	0.111
3	98.0	3.10	19.83	0.245	0.081
4	98.0	3.08	19.83	0.147	0.078
5	98.0	3.20	19.83	0.196	0.099
6	98.0	3.04	19.83	0.147	0.071
7	98.0	1.98	18.38	0.196	0.018
8	98.0	1.98	18.38	0.196	0.019
9	98.0	2.08	18.38	0.196	0.040
10	98.0	2.09	18.25	0.196	0.054
11	98.0	1.95	18.25	0.196	0.025
12	98.1	2.22	18.38	0.196	0.046
13	98.1	2.09	18.38	0.196	0.019
14	98.2	3.40	19.45	0.245	0.138
15	98.4	3.86	19.83	0.147	0.139

NOTE: * All pressure differentials such that cavity pressure is less than vapor bomb pressure by the amount tabulated.

TABLE II

CAVITATION NUMBERS AND CAVITY PRESSURE MEASUREMENTS FOR WATER EXPERIMENTS

Initial Air Content: 1.9 ppm

Barometric Pressure: 29.41 in. Hg

Cavity Length: Indefinite

Run	T $^{\circ}C$	System Pressure Above Atmospheric in. Hg	Flow Velocity in Test Section ft/sec	Cavity Pressure Differential* lb/in^2	Cavitation Number k
1	98.2	4.79	19.30	0.294	0.439
2	98.6	5.45	19.50	0.294	0.452
3	99.0	5.28	19.37	0.294	0.354
4	99.0	5.02	19.45	0.245	0.296
5	99.0	5.38	19.37	0.245	0.373
6	99.2	5.38	19.30	0.294	0.338
7	99.2	5.52	19.45	0.294	0.344
8	99.4	5.65	19.41	0.294	0.336

* All pressure differentials are such that cavity pressure is less than vapor bomb pressure by the amount tabulated.

TABLE III

CAVITATION NUMBERS AND CAVITY PRESSURE MEASUREMENTS FOR WATER EXPERIMENTS

Initial Air Content: 1.4 ppm

Barometric Pressure: 29.52 in. Hg

Cavity Length: Indefinite

Run	T °C	System Pressure Above Atmospheric in. Hg	Flow Velocity in Test Section ft/sec	Cavity Pressure Differential* lb/in^2	Cavitation Number k
1	31.0	-24.00	19.24	0.0	0.435
2	31.2	-23.90	19.30	0.0	0.440
3	32.4	-23.61	19.56	0.025	0.435
4	74.5	-13.34	19.43	0.025	0.439
5	74.6	-13.27	19.43	0.025	0.445
6	75.0	-12.87	19.57	-	0.463
7	97.2	+ 2.00	18.91	-	0.210
8	97.2	+ 1.81	18.91	-	0.147
9	97.2	+ 2.00	18.90	-	0.182
10	98.0	+ 2.66	18.83	-	0.148
11	99.4	+ 4.31	19.04	-	0.146

* All pressure differentials are such that cavity pressure is less than vapor bomb pressure by the amount tabulated.

TABLE IV

CAVITATION NUMBERS AND CAVITY PRESSURE MEASUREMENTS FOR WATER EXPERIMENTS

Initial Air Content: 0.8 ppm

Barometric Pressure: 29.28 in. Hg

Cavity Length: Indefinite

Run	T ^oC	System Pressure Above Atmospheric in. Hg.	Flow Velocity in Test Section ft/sec	Cavity Pressure Differential* lb/in^2	Cavitation Number k
1	98.8	5.08	19.83	0.098	0.258
2	99.0	5.59	20.06	0.098	0.299
3	99.0	5.44	19.97	0.000	0.281
4	99.3	5.99	19.99	0.098	0.313
5	99.4	6.04	19.83	0.098	0.321
6	105.8	12.85	19.99	0.147	0.104
7	105.8	12.76	19.83	0.196	0.100
8	105.8	13.08	19.93	0.196	0.153
9	105.9	13.08	19.93	0.196	0.129
10	109.3	17.81	19.73	0.196	0.123
11	109.5	18.10	19.67	0.147	0.126
12	109.5	18.17	19.81	0.196	0.120
13	109.7	18.38	19.83	0.196	0.104
14	114.4	25.67	19.67	0.147	0.062
15	114.4	26.16	19.90	0.147	0.124
16	114.6	26.08	19.89	0.147	0.044
17	114.8	26.38	19.99	0.147	0.031
18	118.3	32.96	19.99	0.147	0.064
19	118.4	33.04	19.83	0.147	0.055
20	118.5	33.17	19.83	0.147	0.050
21	118.6	33.60	20.10	0.147	0.066

* All pressure differentials are such that cavity pressure is less than vapor bomb pressure by the amount tabulated.

TABLE V

CAVITATION NUMBERS FOR WATER EXPERIMENTS

WITH CAVITIES OF FIXED LENGTH

Initial Air Content: 3.9 ppm

Barometric Pressure: 29.36 in. Hg.

Run	T °C	System Pressure Above Atmospheric in. Hg	Flow Velocity in Test Section ft/sec	Cavity Length inches	Cavitation Number k
1	96.5	2.48	17.92	13/16	0.541
2	97.5	4.19	19.28	13/16	0.461
3	98.8	2.57	14.68	13/16	0.537
4	106.7	15.15	18.51	13/16	0.519
5	110.7	19.29	16.79	13/16	0.405
6	114.5	28.69	19.75	13/16	0.642
7	115.5	29.44	19.83	13/16	0.387
8	96.1	2.48	19.04	1 3/8	0.449
9	98.6	5.37	19.09	1 3/8	0.484
10	99.0	2.61	14.54	1 3/8	0.505
11	106.5	15.00	19.37	1 3/8	0.413
12	110.8	19.64	16.79	1 3/8	0.454
13	114.5	29.05	20.16	1 3/8	0.596
14	115.8	29.94	19.83	1 3/8	0.381

TABLE VI

CAVITATION NUMBERS FOR WATER EXPERIMENTS

WITH CAVITIES OF FIXED LENGTH

Initial Air Content: 1. 2 ppm

Barometric Pressure: 29. 40 in. Hg

Run	T °C	System Pressure Above Atmospheric in. Hg	Flow Velocity in Test Section ft/sec	Cavity Length inches	Cavitation Number k	Fig. No.
1	98. 1	4. 98	18. 42	13/16	0. 606	8
2	105. 6	13. 51	18. 84	13/16	0. 422	9
3	109. 9	20. 32	19. 75	13/16	0. 414	10
4	114. 7	27. 28	19. 17	13/16	0. 328	11
5	118. 2	33. 82	18. 58	13/16	0. 447	12
6	97. 9	4. 60	18. 80	1 3/8	0. 513	13
7	105. 8	13. 98	19. 44	1 3/8	0. 375	14
8	109. 5	19. 47	19. 44	1 3/8	0. 410	15
9	114. 5	27. 20	18. 99	1 3/8	0. 404	16
10	118. 3	33. 42	18. 05	1 3/8	0. 419	17

TABLE VII

CAVITATION NUMBERS FOR FREON-113 EXPERIMENTS WITH CAVITIES OF FIXED LENGTH

Initial Air Content: Unknown

Barometric Pressure: 29.28 in. Hg

Run	T °F	System Pressure Above Atmospheric in. Hg	Flow Velocity in Test Section ft/sec	Cavity Length inches	Cavitation Number k	Fig. No.
1	96.0	0.57	17.52	13/16	0.871	18
2	105.5	0.33	12.89	13/16	1.200	19
3	114.2	5.66	13.22	13/16	1.323	20
4	122.4	11.98	14.07	13/16	1.384	21
5	135.0	20.02	13.32	13/16	1.269	22
6	150.0	37.55	17.39	13/16	1.180	23
7	180.0	68.60	16.79	13/16	0.976	24
8	97.0	0.59	17.45	1 3/8	0.828	25
9	105.0	0.35	13.43	1 3/8	1.110	-
10	114.2	5.32	14.15	1 3/8	0.965	-
11	122.0	11.54	14.70	1 3/8	1.126	26
12	135.0	19.45	13.72	1 3/8	1.156	27
13	150.4	38.77	19.97	1 3/8	0.800	28
14	180.0	70.19	17.98	1 3/8	0.940	29

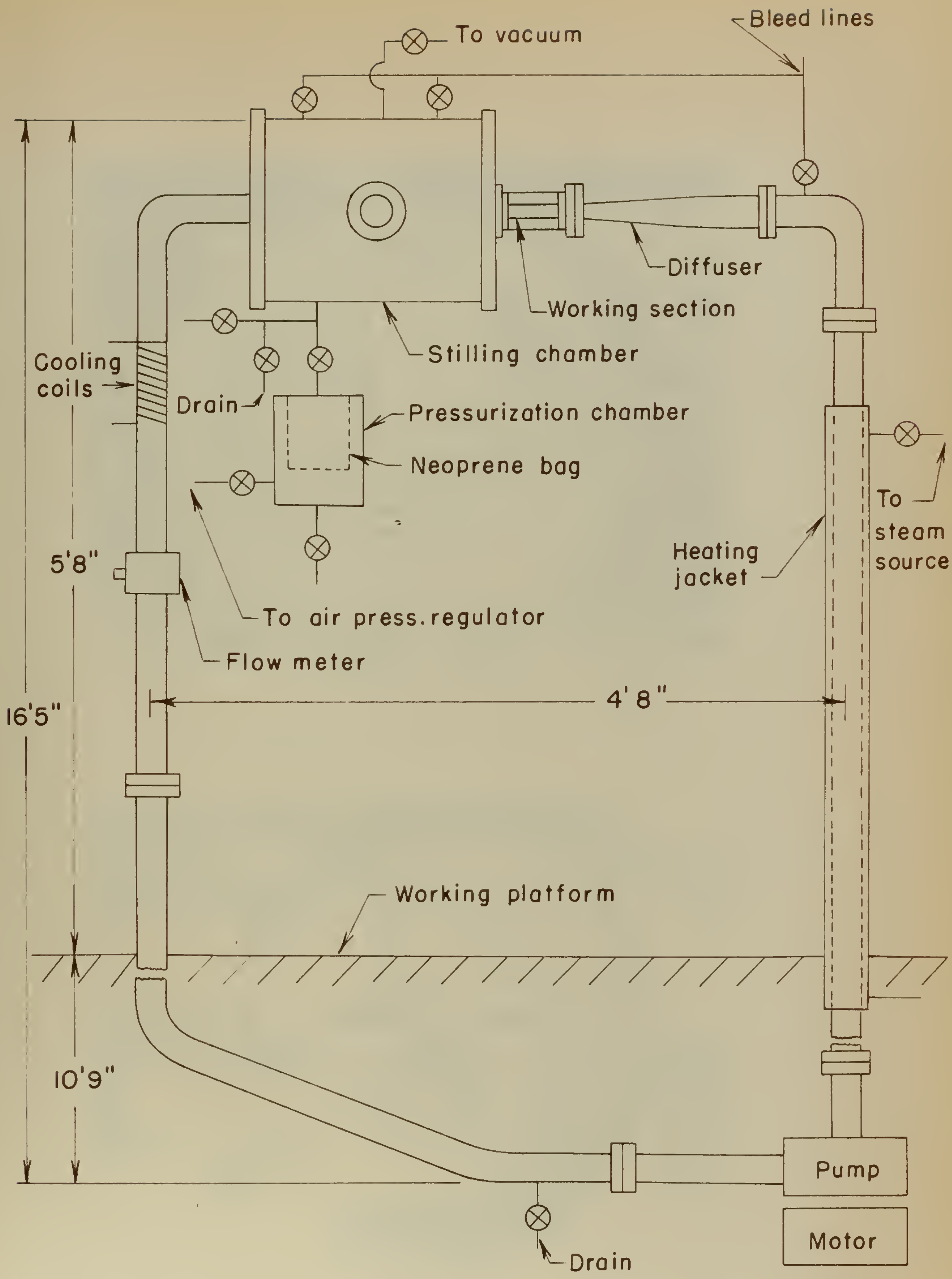

Fig. 1 A view of the test facility showing the arrangement of essential components and overall dimensions. The scale used is approximately one inch to one foot.

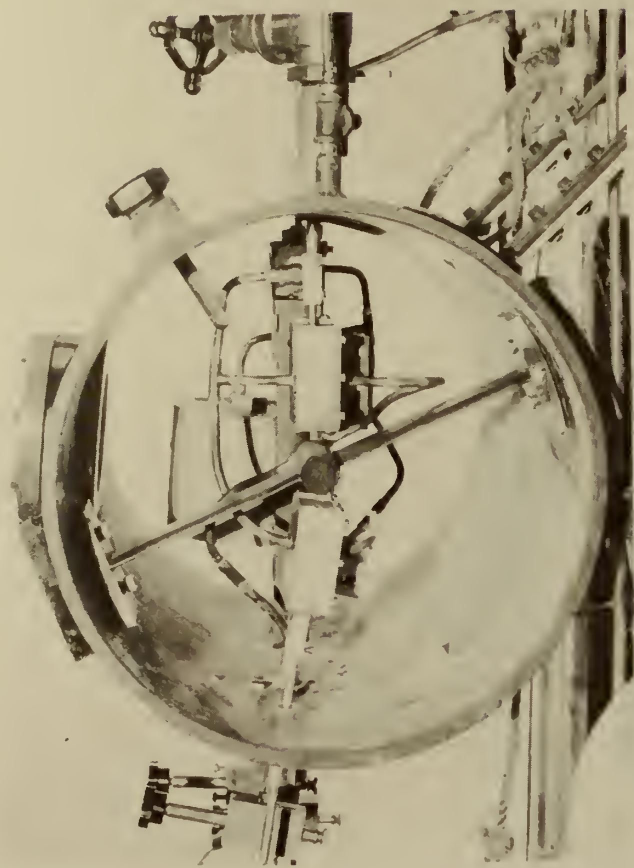

Fig. 2. A view of the stilling chamber showing the probe, probe mount, valves, vapor pressure bomb, and general internal arrangement. The viewer is looking upstream.

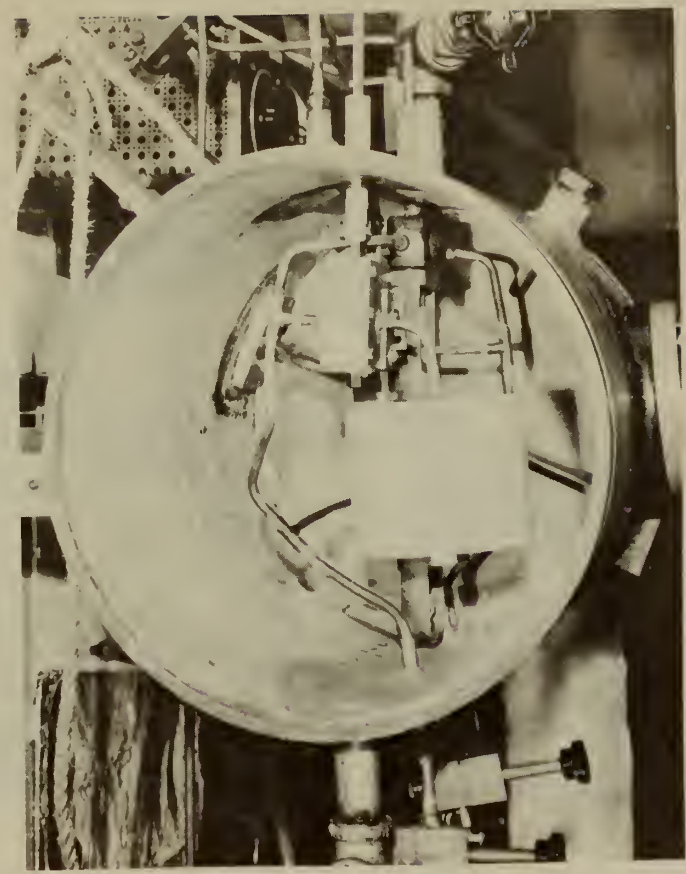

Fig. 3. A view of the stilling chamber showing the general internal arrangement. The vapor pressure bomb is in the foreground. The viewer is looking downstream.

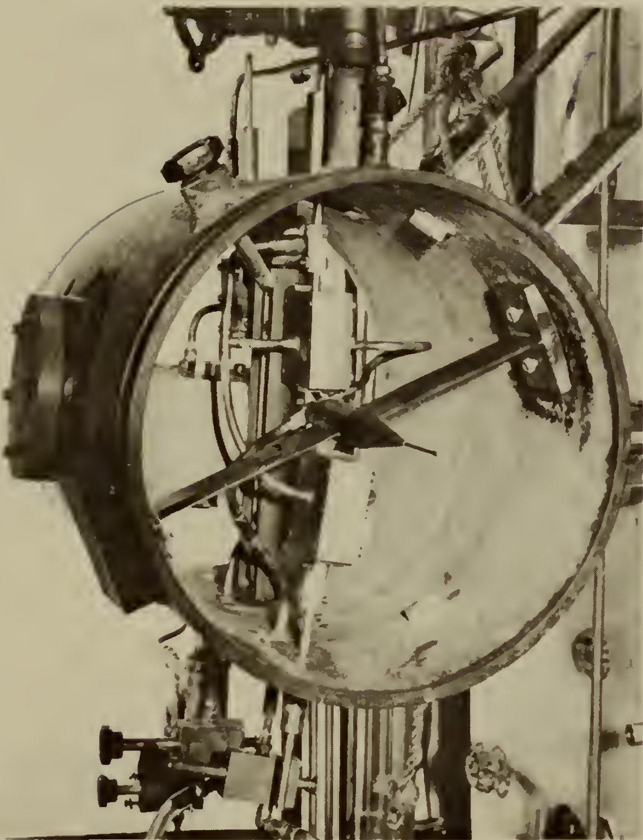

Fig. 4. View of the stilling chamber showing probe and probe mount. The internal mercury manometer can also be seen.

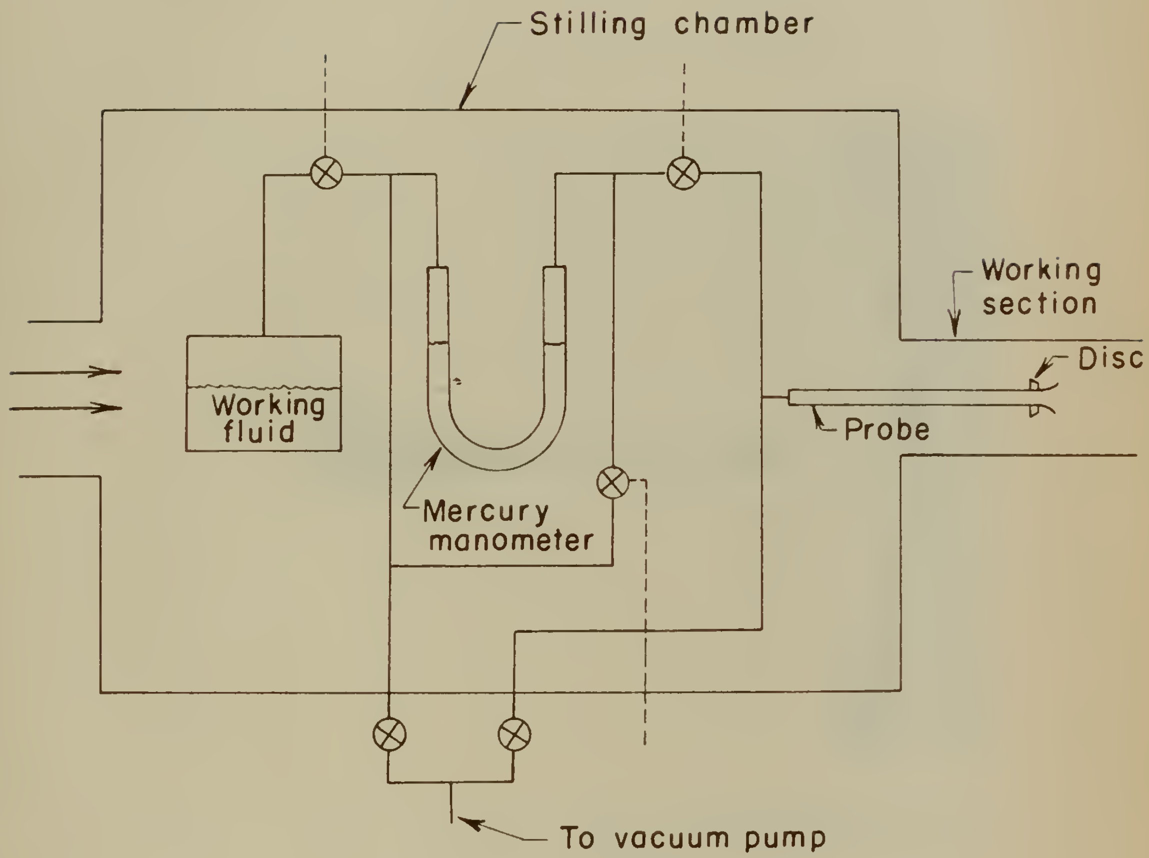

Fig. 5 A schematic drawing of the cavity pressure measuring system within the stilling chamber. The flow proceeds from left to right.

Fig. 6. A close-up view of the probe and turbulence screen. The disc from which the cavity is formed can also be seen.

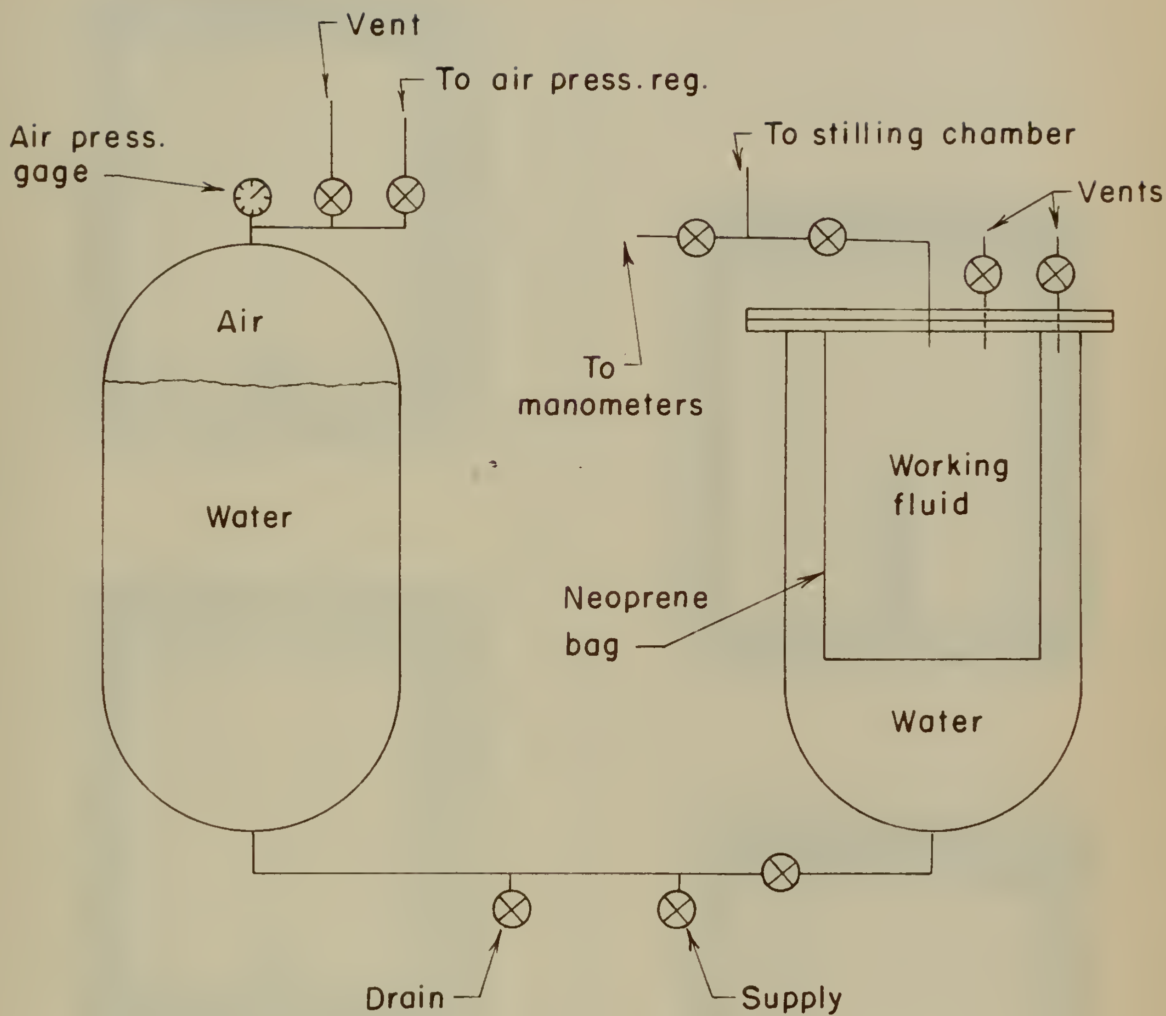

Fig. 7 A schematic drawing of an improved system pressurizing device.

Fig. 8. Water cavity. T=98.1°C, v=18.42 ft/sec, ℓ=13/16 in.

Fig. 9. Water cavity. T=105.6°C, v=18.84 ft/sec, ℓ=13/16 in.

Fig. 10. Water cavity. T=109.9°C, v=19.75 ft/sec, ℓ=13/16 in.

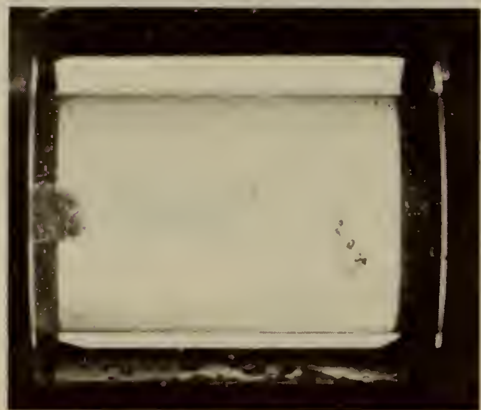

Fig. 11. Water cavity. T=114.7°C, v=19.17 ft/sec, ℓ=13/16 in.

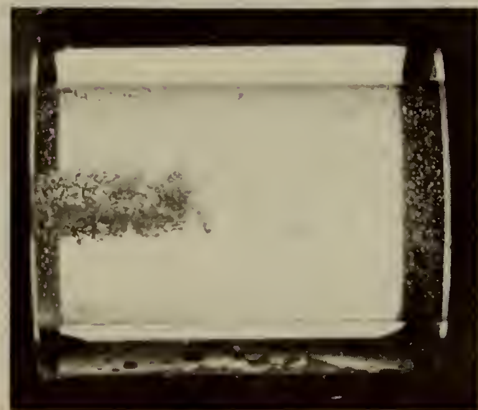

Fig. 12. Water cavity. T=118.2°C, v=18.58 ft/sec, ℓ=13/16 in.

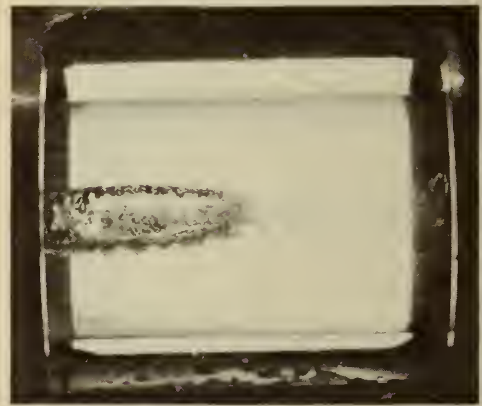

Fig. 13. Water cavity. T=97.9°C, v=18.80 ft/sec, ℓ=1 3/8 in.

Fig. 14. Water cavity. T=105.8°C, v=19.44 ft/sec, ℓ=1 3/8 in.

Fig. 15. Water cavity. T=109.5°C, v=19.44 ft/sec, ℓ=1 3/8 in.

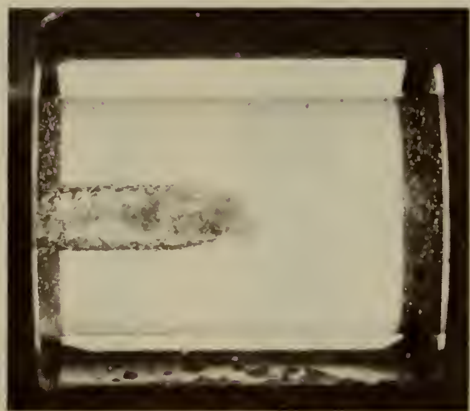

Fig. 16. Water cavity. T=114.5°C, v=18.99 ft/sec, ℓ=1 3/8 in.

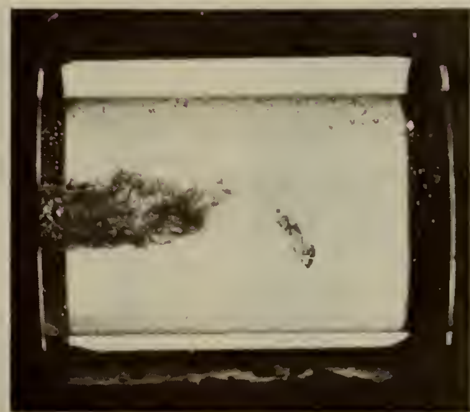

Fig. 17. Water cavity. T=118.3°C, v=18.05 ft/sec, ℓ=1 3/8 in.

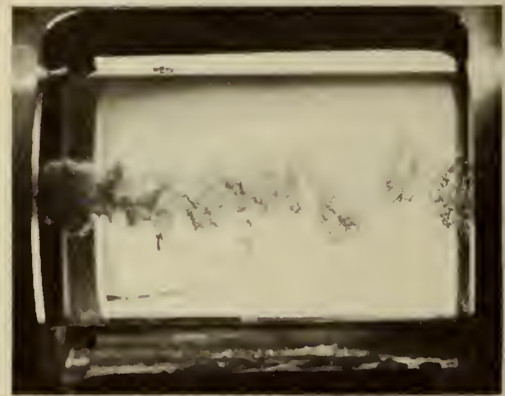

Fig. 18. Freon cavity. T=96.0°F, v=17.52 ft/sec, ℓ=13/16 in.

Fig. 19. Freon cavity. T=105.5°F, v=12.89 ft/sec, ℓ=13/16 in.

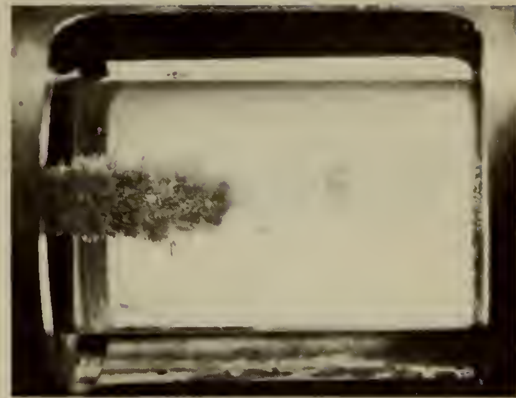

Fig. 20. Freon cavity. T=114.2°F, v=14.15 ft/sec, ℓ=13/16 in.

Fig. 21. Freon cavity. T=122.4°F, v=14.07 ft/sec, ℓ=13/16 in.

Fig. 22. Freon cavity. T=135.0°F, v=13.82 ft/sec, ℓ=13/16 in.

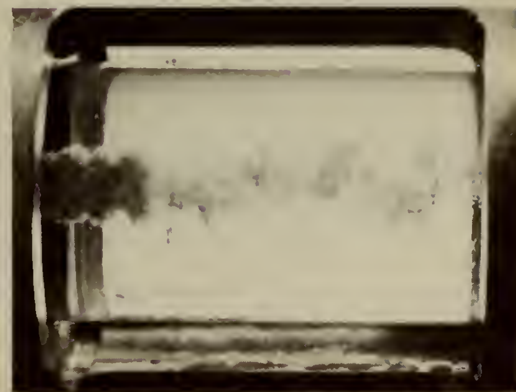

Fig. 23. Freon cavity. T=150.0°F, v=17.39 ft/sec, ℓ=13/16 in.

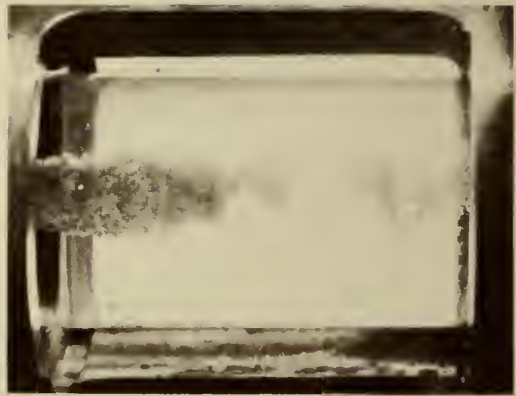

Fig. 24. Freon cavity. T=180.0°F, v=16.79 ft/sec, ℓ=13/16 in.

Fig. 25. Freon cavity. T=97.0°F, v=17.45 ft/sec, ℓ=1 3/8 in.

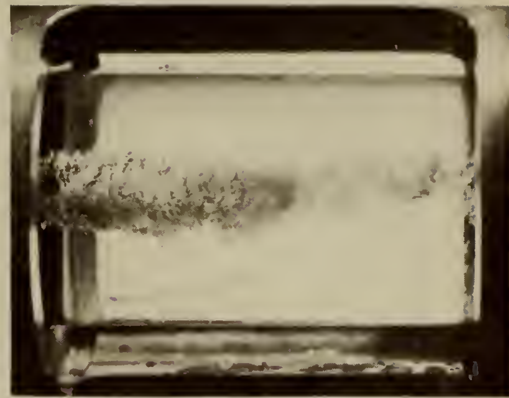

Fig. 26. Freon cavity. T=122.0°F, v=14.70 ft/sec, ℓ=1 3/8 in.

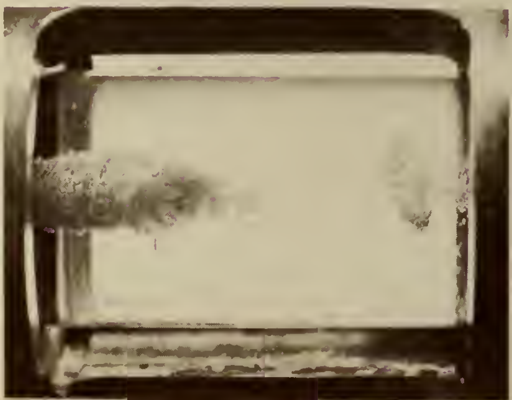

Fig. 27. Freon cavity. T=135.0°F, v=13.72 ft/sec, ℓ=1 3/8 in.

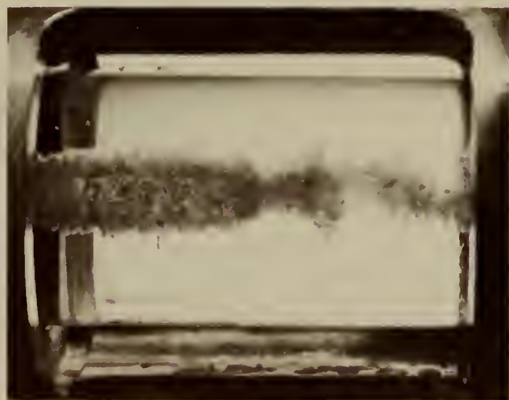

Fig. 28. Freon cavity. T=150.4°F, v=19.97 ft/sec, ℓ=1 3/8 in.

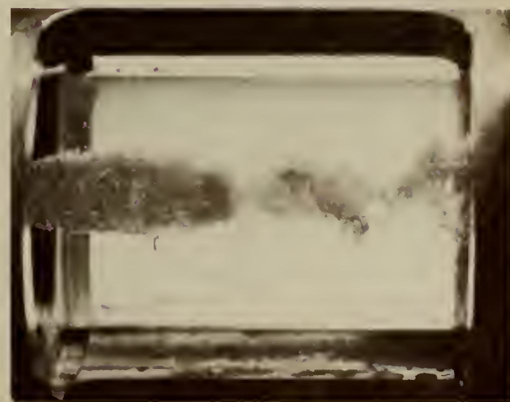

Fig. 29. Freon cavity. T=180.0°F, v=17.98 ft/sec, ℓ=1 3/8 in.